The Halo Black-Hole X-ray Transient XTE J1118+480[1]

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ABSTRACT

Optical spectra were obtained of the optical counterpart of the high latitude ($b \simeq 62^\circ$) soft X-ray transient XTE J1118+480 near its quiescent state ($R \simeq 18.3$) with the new 6.5 m MMT and the 4.2 m WHT. The spectrum exhibits broad, double-peaked, emission lines of hydrogen (FWHM $\simeq 2400$ km s^{-1}) arising from an accretion disk superposed with absorption lines of a late-type secondary star. Cross-correlation of the 27 individual spectra with late-type stellar template spectra reveals a sinusoidal variation in radial velocity with amplitude $K = 701 \pm 10$ km s^{-1} and orbital period $P = 0.169930 \pm 0.000004$ d. The mass function, 6.1 ± 0.3 M$_\odot$, is a firm lower limit on the mass of the compact object and strongly implies that it is a black hole. We estimate the spectral type of the secondary to be K7V–M0V and that it contributes $28 \pm 2\%$ of the light in the 5800-6400 Å region on 2000 November 20 increasing to $36 \pm 2\%$ by 2001 January 4 as the disk fades. Photometric observations (R-band) with the IAC 0.8 m telescope reveal ellipsoidal light variations of full amplitude 0.2 mag. Modeling of the light curve gives a large mass ratio ($\frac{M_1}{M_2} \sim 20$) and a high orbital inclination ($i = 81^\circ \pm 2^\circ$). Our combined fits yield a mass of the black hole in the range $M_1 = 6.0 - 7.7$ M$_\odot$ (90% confidence) for plausible secondary star masses of $M_2 = 0.09 - 0.5$ M$_\odot$. The photometric period measured during the outburst is 0.5% longer than our orbital period and probably reflects superhump modulations as observed in some other soft X-ray transients. The estimated distance is $d = 1.9 \pm 0.4$ kpc corresponding to a height of 1.7 ± 0.4 kpc above the Galactic plane. The spectroscopic, photometric, and dynamical results indicate that XTE J1118+480 is the first firmly identified black hole X-ray system in the Galactic halo.

Subject headings: accretion, accretion disks - binaries: spectroscopic - black hole physics - stars: individual: XTE J1118+480 - X-rays:stars

1. Introduction

X-ray novae or soft X-ray transients comprise a subset of low-mass X-ray binaries (LMXBs) which consist of a late-type secondary star and a neutron star or a black hole exhibiting bright optical and X-ray outbursts which are recurrent on time scales of decades (Tanaka & Lewin 1995; Tanaka & Shibazaki 1996). During their outbursts, they resemble persistent LMXBs in which the light of the secondary star is overwhelmed by a luminous accretion disk surrounding the compact object. After a year or less in some objects, the system returns to quiescence. The secondary

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star now contributes a much larger fraction of the total light and its atmospheric absorption lines become visible in optical spectra. Thus quiescent X-ray novae provide the ideal opportunity to study the nature and dynamical properties of the binary system (see e.g. Charles 1998). These studies have demonstrated that the mass of the compact object in ten X-ray novae (Charles 1998; McClintock 1998; Nova Vel 1993: Filippenko et al. 1999; V4641 Sgr: Orosz et al. 2001) exceeds the theoretical maximum mass of a neutron star (Rhoades & Ruffini 1974) and thus must evidently be a black hole.

A previously unknown X-ray transient, XTE J1118+480, was discovered by the RXTE ASM instrument on 2000 March 29 (Remillard et al. 2000) with an average 2-12 keV X-ray intensity of only 39 mCrab, but with a spectral signature similar to other accreting Galactic black holes. An optical counterpart was identified on March 30 (Uemura et al. 2000) with $V = 12.9$ and confirmed spectroscopically (Garcia et al. 2000). Photometry during the outburst (Patterson 2000; Uemura et al. 2000) revealed a weak modulation with a period of $\simeq 0.1708$ d and an amplitude of 0.055 mag reflecting the probable orbital period of the system. The shape of the light curve and its temporal evolution resembled those of superhumps (Uemura et al. 2000) observed during superoutbursts of short-period cataclysmic variables and outbursts of some other soft X-ray transients (O'Donoghue & Charles 1996), and which correspond to a period only fractionally ($\leq$1–2%) longer than the orbital period.

By 2000 August 31, photometry reported to VSNET indicated that J1118+480 had faded to near its quiescent level of $V \simeq 18.8$. Its high Galactic latitude ($b = +62°$), implying a low value of interstellar absorption ($A_{\rm V}$= 0.04 mag; Hynes et al. 2000), combined with its relatively bright quiescent magnitude makes J1118+480 ideal for detailed study in quiescence, especially at wavelengths not easily observable in other low-latitude transients. In this *Letter*, we present the results of optical spectroscopy and photometry obtained in quiescence beginning in late 2000 November and continuing through 2001 January. A preliminary announcement of our spectroscopic results (Wagner et al. 2000) as well as those obtained by a second group (McClintock et al. 2000) was reported in the IAU Circulars.

2. Observations

We obtained 20 spectra of J1118+480 with the newly upgraded 6.5 m MMT equipped with the blue channel CCD spectrograph on the nights of 2000 November 20 (5 spectra), 30 (9 spectra), and 2001 January 4 (6 spectra). The spectra cover the range $\lambda\lambda$4200-7500 at a spectral resolution of 3.5 Å and a dispersion of 1.1 Å pixel^{-1}. The seeing was typically 1″ and a 1″ wide slit was employed. Each 1440 s exposure was bracketed by a HeNeAr lamp spectrum which led to a wavelength calibration accurate to 5–7 km s^{-1} rms. Spectra of the late-type dwarf stars BD+63°137 (K7), Gliese 239 (M0), Gliese 96 (M0.5), Gliese 154 (M0), and Gliese 388 (M3.5) were obtained using the same instrumental configuration so as to accurately gauge the spectral type of the secondary star and to provide templates for the radial velocity analysis. We note that the first two stars, BD+63°137 and Gliese 239, are classified as K5V and K7 respectively in Simbad. However, based on the depth of their TiO bands and by comparison with very securely classified templates (such as 61 Cyg A & B), we support classifications of K7V and M0V respectively.

We also obtained 7 spectra of J1118+480 with the ISIS red channel of the 4.2 m William Herschel Telescope on La Palma on the night of 2001 January 11. We employed the R316R grating which yields 1.47 Å pixel^{-1} in the range $\lambda\lambda$5820-7320. The slit width was 1.″5 which resulted in a spectral resolution of 4.5 Å. Exposure times were 1200 s and the wavelength calibration provided by internal lamps was checked with respect to night-sky emission lines to be within 10 km s^{-1}. Spectra of the dwarf stars HR 5265 (K3), HR 8085 (61 Cyg B; K5), HR 8086 (61 Cyg A; K7), and Gliese 361 (M1.5) were both employed as radial velocity templates and for spectral classification of the secondary. Accurate absolute photometric calibration was not attempted for either the MMT or WHT spectra due to slit losses.

Time-resolved differential CCD photometry was obtained of J1118+480 in the R-band (λ_c = 6500 Å; FWHM = 1500 Å) on the nights of 2000 December 14, 28, and 2001 January 9 (UT) with the 0.80 m IAC80 telescope at the Observatorio del Teide (Tenerife). We used the Thompson 1024×1024 pixel CCD camera with 2×2 pixel binning giving an image scale of $0\farcs43$ pixel^{-1}. A total of 68 10-minute exposures were obtained in $\sim 2''$ seeing and good transparency, together with bias and flatfield frames to facilitate the standard data reduction procedures. We applied profile fitting photometry to J1118+480 and several nearby comparison stars using IRAF. We also selected comparison stars which were checked for variability during the night and calibrated as field reference stars using Landolt standard stars to place our photometry on an absolute scale. We estimate that our relative photometric accuracy is 0.05 mag. Finally, we measured the position of J1118+480 on a registered average of the frames obtained on December 28. Based on a grid of 22 USNO A2.0 stars, we find that the position of J1118+480 is R.A. = $11^h18^m10\fs84$, Decl. = $+48°02'12\farcs9$ (equinox 2000.0, accuracy $\pm0\farcs3$).

3. Results

3.1. Spectroscopy

The individual spectra of J1118+480 exhibit broad Balmer emission lines arising from an accretion disk superposed with absorption lines or bands of Mg*b* λ5175, Na D, and of TiO. Radial velocities were extracted by cross-correlating the individual normalized spectra over the range 5800-6400 Å of J1118+480 with our grid of templates using routines in both IRAF and locally developed software packages. Phasing of the radial velocities on the photometric period (0.17 d) yielded a nearly sinusoidal variation in radial velocity indicating that the photometric period was close to the orbital period.

To obtain an accurate measurement of the orbital period and determine the best-fitting spectral type of the secondary, successive circular orbits with periods ranging from 0.169000 to 0.171000 d were fit to the radial velocity data defined by the grid of templates. We found that our best cross-correlations and circular orbit solutions corresponded to spectral types of K5V-M0V and an orbital period of 0.169930 ± 0.000004 d ($\chi^2_\nu = 4.5; 23$ dof), i.e. 0.5% shorter than the outburst photometric period of Uemura et al. (2000). We have scaled the velocity errors by a factor of $\sqrt{4.5}$ in order to give $\chi^2_\nu = 1.0$.

The radial velocity curve of the secondary star is shown in Figure 1 (upper panel). A sine fit to the data gives: $P = 0.169930 \pm 0.000004$ d; $\gamma = -15 \pm 10$ km s^{-1}; $K = 701 \pm 10$ km s^{-1}; $T_0 =$ HJD $2,451,868.8916 \pm 0.0004$ (2000 November 20.3916 UT), where T_0 corresponds to absolute phase 0.0 or inferior conjunction of the secondary star. Orbital smearing will systematically underestimate the true velocity amplitude. For these data at the peak of the radial velocity curve, we estimate this effect to be no more than 1.6% or about 11 km s^{-1}. The mass function is

$$f(M) = \frac{(M_1 \sin i)^3}{(M_1 + M_2)^2} = \frac{PK^3}{2\pi G} = 6.1 \pm 0.3\ M_\odot,$$

where G is the Gravitational Constant. The mass function implies a lower limit to M_1 of $M_1 = 6.1\ M_\odot$. This greatly exceeds the maximum mass of a neutron star (Rhoades & Ruffini 1974) and implies that the compact object is probably a black hole.

In Figure 2, we show the spectrum of J1118+480 on 2000 November 30, formed by averaging the individual Doppler-corrected spectra (total integration time 3.6 hr) to the rest frame of the secondary star, together with the spectra of a M0.5V (Gliese 96) and K7V (BD+63 137) star for comparison, bracketing the likely spectral type of the J1118+480 secondary. The absorption features of the secondary star are now sharp and readily apparent, but this process smears out the emission lines arising from the accretion disk surrounding the compact object. However, comparison of the spectrum with our templates indicates that the spectrum of J1118+480, apart from the emission lines, is too blue. Also, the absorption lines are much weaker relative to an uncontaminated K7V star, thereby suggesting a substantial contribution from the quiescent accretion disk. This contribution, particularly the velocity information in the broad and complex Hα emission line, will be discussed in a forthcoming companion paper (Zurita et al. 2001).

To estimate the fraction of the observed flux arising from the secondary star and disk separately, we subtracted fractions of our grid of templates from the Doppler-corrected spectra of J1118+480 for each night and performed a χ^2 minimization of the residuals in the range 5800-6400 Å. This region overlaps both the MMT and

WHT spectra and is rich in metallic absorption lines. The templates were broadened by convolution with Gaussian passbands to account for small differences in instrumental resolution between the MMT and WHT and the effects of orbital smearing due to the length of our exposures. We find that the best-fitting templates are K7V-M0V and that the secondary contributes $\simeq 32\%$ of the total light in this spectral region. Our results are consistent with those obtained by McClintock et al. (2001) close to our earlier observations. Specifically, we find that for 2000 November 20, 30, and 2001 January 4 that the secondary contributes $28 \pm 2\%$, $28 \pm 2\%$, $36 \pm 2\%$ respectively, so that it appears that the disk luminosity is still declining and the system may not yet be fully quiescent.

3.2. Photometry

To interpret the optical light curves, we used a model that includes a Roche lobe-filling secondary star, a concave accretion disk, and mutual eclipses of the disk and the secondary star. This X-ray binary model and the fitting procedure are fully described in Shahbaz et al. (2001). The model parameters are the binary inclination i, the mass ratio q ($=M_1/M_2$), the mean temperature $\bar{T}$ and gravity $\log \bar{g}$ of the secondary, the gravity darkening exponent β, the accretion disk radius R_{disk} [defined as the fraction of the distance to the inner Lagrangian point (R_{L_1})], the flare angle of the accretion disk (θ), the temperature at the outer disk edge T_{disk}, and the exponent on the power-law radial temperature distribution η. We fixed $A_{\rm V}$ at 0.04 mag (Hynes et al. 2000).

From our optical spectroscopy, the secondary star has an observed spectral type of K7V-M0V, so we fixed $\bar{T}$ at 4250 K and $\log \bar{g}$ at 5.0, appropriate for K7V. Since the late-type star is convective, we take $\beta = 0.08$ (Lucy 1967). The accretion disk is assumed to be optically thick and geometrically thin, and so we set the flare angle of the disk to be 0.04 radians and η to be -0.75 (appropriate for a steady-state disk; Pringle 1981). We can use the value for the mass function and the observed spectral type to place an upper limit to the binary mass ratio. The mass function gives a lower limit to M_1 ($\geq 6.1\ M_\odot$) and the mass for the main sequence spectral type of the secondary gives an upper limit for M_2 ($\lesssim 0.52\ M_\odot$). Thus we obtain a lower limit for the mass ratio of $q \gtrsim 12$ and so we assume $q = 20$ in our model (the results are largely insensitive to this value). Note that such high mass ratios are also supported by our small "superhump period" excess in the model of Mineshige et al. (1992).

The phase-averaged R-band light curve of J1118+40 is shown in the lower panel of Figure 1 together with our best-fitting model for the parameters i, R_{disk}, T_{disk}, a phase shift,the distance d, and normalization. The data were folded using the spectroscopic period and epoch given above (i.e. phase 0 is defined as superior conjunction of the compact object; note that this is *not* how McClintock et al. (2001) have defined their phase convention). We find a best fit at $i = 81 \pm 2$ degrees, $R_{disk} = 0.8 R_{L1}$, $\mathrm{T}_{disk} = 3906$ K, and $d = 1.8 \pm 0.3$ kpc (2σ). A one–dimensional grid search was performed to determine the uncertainties of the fitted parameters. The model predicts a veiling of 76% which is consistent with the values derived from our optical spectroscopy. It should be noted that with such a high inclination one might normally expect to see eclipses of the secondary and accretion disk. However, given the extreme mass ratio, one only expects shallow eclipses of the secondary and disk (Figure 1).

In addition, we find a small phase shift (0.02 ± 0.04; $\sim$4.6 min) between the photometric light curve and the spectroscopically defined phase. Such an effect (at the level of 12 ± 2 min) is seen by McClintock et al. (2001) who, as we do, discount the possibility of an instrumental origin. It should be noted that McClintock et al. do not formally fit their data with an ellipsoidal model, but show one that "matches" their data, albeit with a very obvious phase offset of 12 min. Their model combines an ellipsoidal modulation with a constant contribution (at the 66% level) from an accretion disk. We believe that this phase shift is actually due to a temporally varying, *asymmetrically* emitting disk component. In a companion paper (Shahbaz et al. 2001), we model the quiescent light curves of the neutron star SXT XTE J2123-058 (it has a 6 hr orbital period and high orbital inclination) which are remarkably similar in shape to that of McClintock et al. (2001) by employing such a disk component.

4. Discussion

The mass of the secondary star can be constrained by making assumptions regarding its evolutionary state. An upper limit to M_2 can be obtained by using the mass of a main sequence star of the same spectral type ($M_2(MS)$), while the secondary would not have left the main sequence if its mass were less than the Schonberg-Chandrasekhar limiting value of $0.17M_2(MS)$. Thus from the observed spectral type of K7V, M_2 must lie in the range 0.09–0.50 $M_\odot$. Combining this constraint with our measured values for $f(M)$ and i, we show in Figure 3 the inferred range for M_1 which is 6.0–7.7 $M_\odot$ (2σ). The uncertainties were determined by Monte Carlo simulation, in which we draw Gaussian–distributed random values for the observed quantities, with a mean and variance the same as the observed values.

Over the past 10 years dynamical studies have established that several X-ray novae contain compact objects with masses significantly larger than the maximum mass of a normal neutron star ($\simeq$ 3.2 $\mathrm{M}_\odot$; Rhoades & Ruffini 1974) such as V404 Cyg ($\gtrsim$ 6.1 $M_\odot$; Casares and Charles 1994); QZ Vul 1988 ($\gtrsim$ 5.0 $M_\odot$; Casares, Charles, & Marsh 1995; Filippenko, Matheson, & Barth 1995; Harlaftis, Horne, & Filippenko 1996); and V2107 Oph 1977 ($\gtrsim$ 4.7 $\mathrm{M}_\odot$; Remillard et al. 1996; Filippenko et al. 1997; Harlaftis et al. 1997) implying that they are black holes. The large mass function and well-determined mass of the compact object in XTE J1118+480 derived here indicates that it almost certainly contains a black hole rather than a neutron star. Recently Bailyn et al. (1998) have noted that the masses of black holes in LMXBs are strongly peaked at $\sim$7$\mathrm{M}_\odot$, and our mass determination is consistent with this result.

We can estimate the distance to J1118+480 by constraining the secondary's size from our photometric modeling by using the Eaton & Poe (1984) redetermination of the Barnes-Evans relation, which relates V-band flux at the star and color for stars with measured angular diameters. From our light curve the mean R is 18.17, of which 76% is from the disk according to our model fits. This implies that the secondary has $R = 19.72$, and if its spectral type is K7V ($V - R = 1.15$; from our spectroscopy), then $V_0 = 20.83$ (assuming $A_{\mathrm{V}}= 0.04$). From V_0 and the $V - R$ color, we then estimate that the angular diameter of the secondary is 1.94×10^{-3} mas (Eaton & Poe 1984). From the Eggleton (1983) approximation of the volume radius of the Roche lobe of the secondary star, we find that the size of the Roche-lobe is $R_2 = 0.17a$ for $q = 20$ and where a is the separation of the center of mass of the two components. From our total mass estimate of 7 $\mathrm{M}_\odot$ and Kepler's third law, we find that $a = 2.37R_\odot$, and thus $d = 1.9 \pm 0.4$ kpc. The error in d is dominated by the uncertainty in the secondary spectral type. We find that for $b = +62°$, $z = 1.7\pm0.4$ kpc, where z is the vertical distance above the Galactic plane.

Thus, XTE J1118+480 is the first firmly identified black hole X-ray binary system in the Galactic halo. This fact is quite remarkable compared with the distribution of the black-hole LMXBs (White & van Paradijs 1995) where the mean z is around 400 pc (and that is dominated by a single object, H1705-25, at $\sim$950 pc). This is less than half that of the neutron star systems, which is explained by the additional "kick" velocity received in the formation of the neutron star. To place J1118+480 at its current location in this scenario would have required an enormous velocity out of the plane, making its almost zero systemic velocity very unlikely. Furthermore, we find no evidence of a large proper motion of J1118+480 ($\lesssim$ 10 mas $\mathrm{yr}^{-1}; 2\sigma$) since its position measured during the outburst (Uemura et al. 2000; Masi 2000) and our position near quiescence (see §2) as compared with its position measured on an archival POSS-I plate obtained $\sim$ 47 yrs ago (from the USNO A2.0 and APM Palomar Schmidt sky catalog; Lewis & Irwin 1996) all agree to within the astrometric errors. This object therefore presents interesting challenges and constraints on the formation and evolution of SXTs.

It is also interesting to consider whether there might be an additional population of such high z BH LMXBs in the Galaxy. J1118+480 is one of the closest, yet is also one of the (intrinsically) X-ray weakest of the LMXB X-ray transients and has a low L_X/L_{opt} ratio. Hence, further examples would almost certainly have gone undetected due to their X-ray faintness and high latitude (the most sensitive X-ray monitoring is undertaken in the plane and around the Galactic center). However, Hynes et al. (2000) discussed the possibility that the intrinsic weakness of the X-rays relative to the optical might be due to the high inclination, making this system akin to the Galactic ADC (accretion disk corona) sources, and hence other high latitude systems would be expected to be much brighter X-ray sources. While this appears to have been borne out by our inference of the (extremely) high inclination of 81°, there are several difficulties with this argument. There was an absence of any X-ray modulation in outburst, although the secondary is so small that it might always be completely shadowed by the disk and hence unable to produce any significant modulation. (Note that this interpretation is testable via higher time resolution photometry as the eclipse should be visible; see Figure 1 at phase 0.0). More seriously, the models considered by Esin et al. (2001) and fit to the exceptionally wide wavelength spectra of J1118+480 obtained during outburst have ruled out the ADC model since the source was in the low/hard state. This is further supported by the direct X-ray observation of ∼0.1Hz QPOs (Wood et al. 2000).

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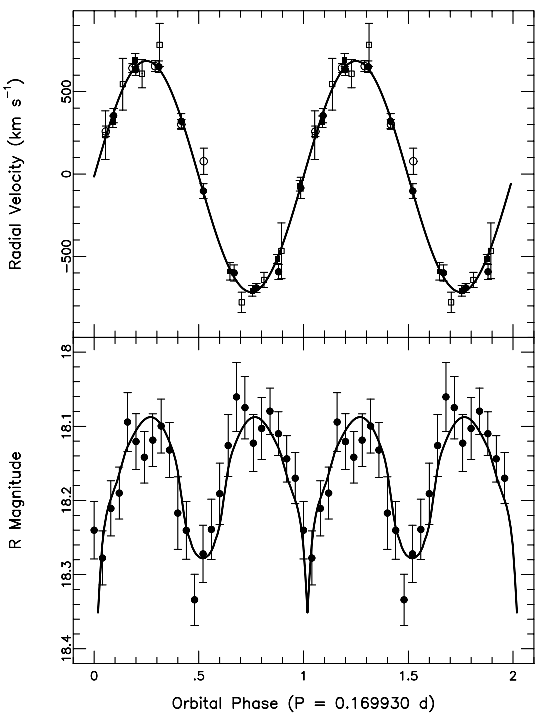

Fig. 1.— Upper: Folded radial velocities of XTE J1118+480 and the best-fitting sinusoid. Open circles indicate the data obtained on 2000 November 20 (MMT), filled circles on 2000 November 30 (MMT), filled squares on 2001 January 4 (MMT), and open squares on January 12 (WHT) respectively. Lower: The phase folded R-band light curve of XTE J1118+480. The solid line shows the best–fit light curve solution. The sharp dip at phase 1.0 might be due to a grazing eclipse of the accretion disk by the secondary star. Two orbital cycles are shown for clarity.

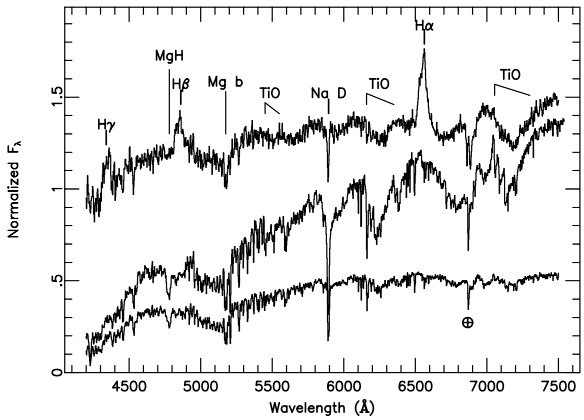

Fig. 2.— Upper: Doppler-corrected rest-frame spectrum of XTE J1118+480 obtained on 2000 November 30. Middle: M0.5V spectrum (Gliese 96). Lower: K7V spectrum (BD+63°137). We estimate that the secondary is K7V-M0V in J1118+480. The spectra have been offset for clarity. The prominent spectral features are indicated.

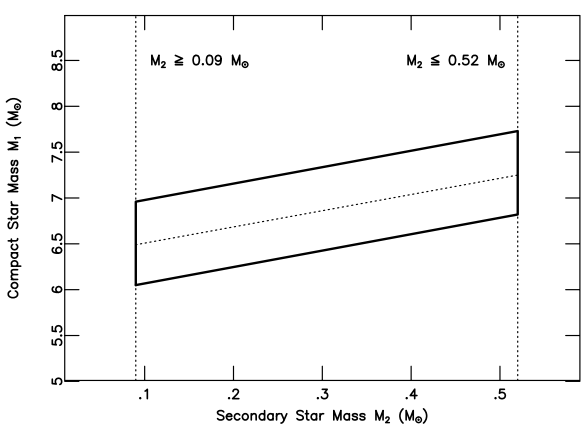

Fig. 3.— The mass of the compact object as a function of the secondary star mass. The two solid lines represent the 90% confidence limits for the probable mass range (the central dashed line being the best fit value). The two dashed vertical lines are upper and lower limits to the secondary star mass from other considerations (see text).